AN11617

SSL6203TW 120 V 12 W linear LED driver

Rev. 1 — 13 April 2015 Application note

Document information

Info	Content
Keywords	SSL6203TW, TRIAC dimmable, linear LED driver, incandescent dimming curve
Abstract	This application note is a guide for the design and layout of a linear LED driver used in dimmable Solid-State Lighting (SSL) LED lighting. This document describes the theory of linear LED drivers, the benefit of SSL6203TW patented structure (81644813; US 20140125235 A1; US 20130257282 A1; CN103384431A; EP2645816A1). It also describes the circuit design to get good dimmer compatibility and incandescent dimming curve.

Revision history

Rev	Date	Description
v.1	20150413	first issue

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1. Introduction

Linear LED drivers are a relatively new way of driving LEDs. The driver connects high-voltage (HV) LEDs directly to the mains when sufficient voltage is available. More HV LEDs are connected in series as more mains voltage is available.

To optimize LED utilization and achieve a balanced optical and thermal lamp design, the NXP Semiconductors linear LED driver employs switches.

A linear LED driver enables very small form factor LED lamps because it incorporates fewer components than traditional switched-mode LED drivers. The linear LED driver is small enough to be integrated on the LED plate. Making performance compromises and removing components can further reduce the driver size.

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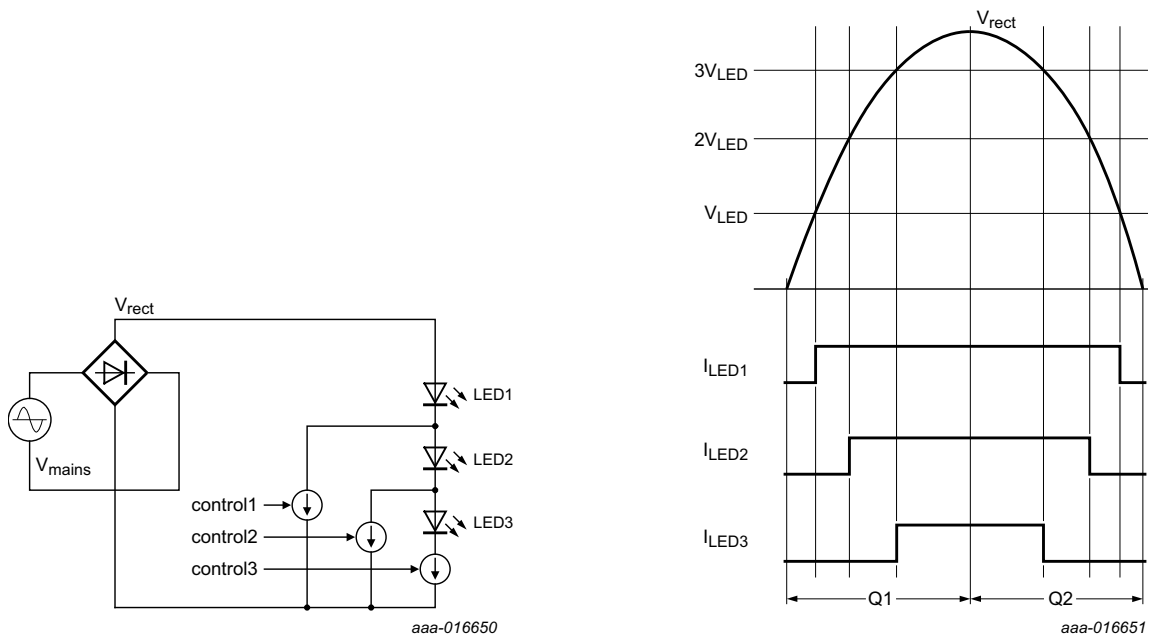
2. High-voltage linear driver

Depending on the instantaneous rectified mains voltage (V_{rect}), linear LED drivers connect one or multiple HV LED strings to the mains. Figure 1 shows the concept of a conventional linear LED driver. When the mains voltage is high enough to turn on one LED string ($V_{rect} > V_{LED}$), the driving current starts flowing through that LED. Similarly, if the mains voltage is high enough, LEDs 2 and 3 are turned on.

When the mains voltage decreases, LED3 is turned off when $V_{rect} < 3 * V_{LED}$, LED2 when $V_{rect} < 2 * V_{LED}$. Finally, when $V_{rect} < V_{LED}$, LED1 is turned off. A significant drawback is that LED1 remains turned on for a relatively long time, while LED3 is only turned on for a relatively short time. The impact on the application is that LED1 has both a higher average current and a higher temperature, leading to a lower efficacy and a lower lifetime. Simultaneously, LED3 is underutilized. So this system has a poor LED utilization.



a. Circuit

b. Waveform

Fig 1. Conventional linear LED driver

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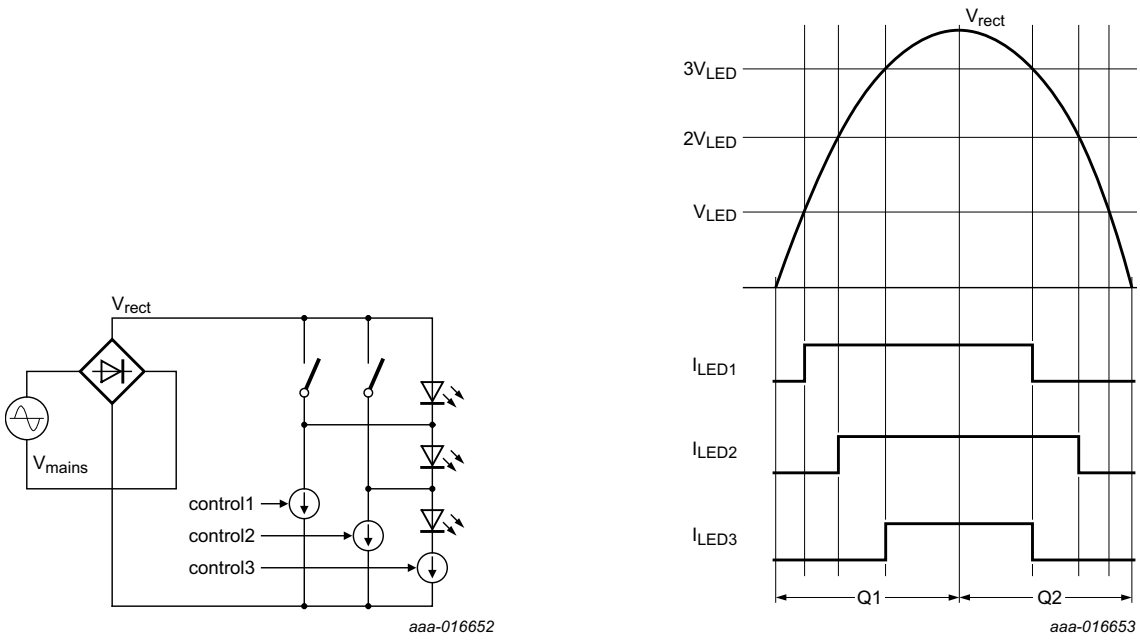
2.1 Improved LED utilization

To overcome the problem that conventional linear drivers have, the NXP Semiconductors linear LED driver uses switches. Switches are added to disable LEDs 1 and 2. Figure 2 shows this concept. In the first quarter of the mains cycle, LED1, LED2, and LED3 turn on in the same way as with the conventional LED driver. However, in the second quarter a switch is used to turn off LED1 when $V_{rect} < 3 * V_{LED}$. A second switch is used to turn off LED2 when $V_{rect} < 2 * V_{LED}$.

The result is that the on-times of the three LEDs have now become similar, as have their efficacy, light output, and temperature. It simplifies the design and so reduces the overall system cost.



a. Circuit

b. Waveform

Fig 2. NXP Semiconductors linear LED driver

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2.2 Improved quality of light

While the system shown in Figure 2 has balanced LED utilization, it still has 100 % light ripple at 100 Hz. The LEDs cannot be driven when $V_{rect} < V_{LED}$. So, around the zero crossings of the mains voltage, all LEDs are off. The result is a poor quality of light.

To solve this issue, capacitors can be placed in parallel with the LEDs. Figure 3 shows this concept. This solution causes the LED currents to be averaged. It prevents that the LEDs turn off completely around the mains zero crossings. The remaining current ripple is a design parameter. Choosing a proper capacitance value can set this parameter. To prevent that the capacitors are discharged at low mains voltages or when the switches are used, blocking diodes must be placed as well.

An additional advantage of using the electrolytic capacitors is that the LEDs are driven at a lower current, which means the efficacy of the LEDs is slightly higher. The NXP Semiconductors linear LED driver IC works both with and without capacitors being added to the system.

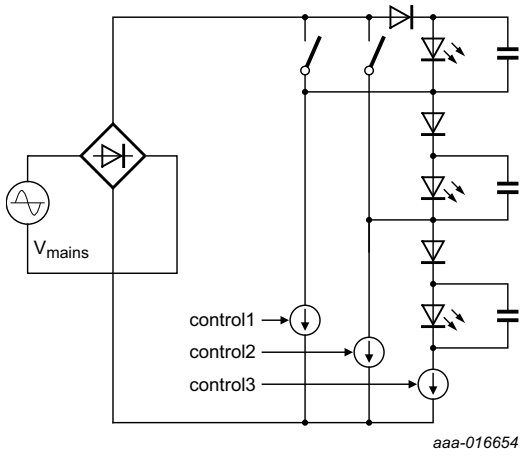

Fig 3. NXP Semiconductors linear LED driver with electrolytic capacitors

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2.3 Improved thermal performance

The mismatch between the cumulative LED voltage and the mains voltage mainly determines the efficiency of linear LED drivers (see Figure 4). Because the same current is drawn from the mains regardless of how many HV LEDs are active, the dissipation in the LED driver varies with the difference between the cumulative LED voltage and the instantaneous mains voltage.

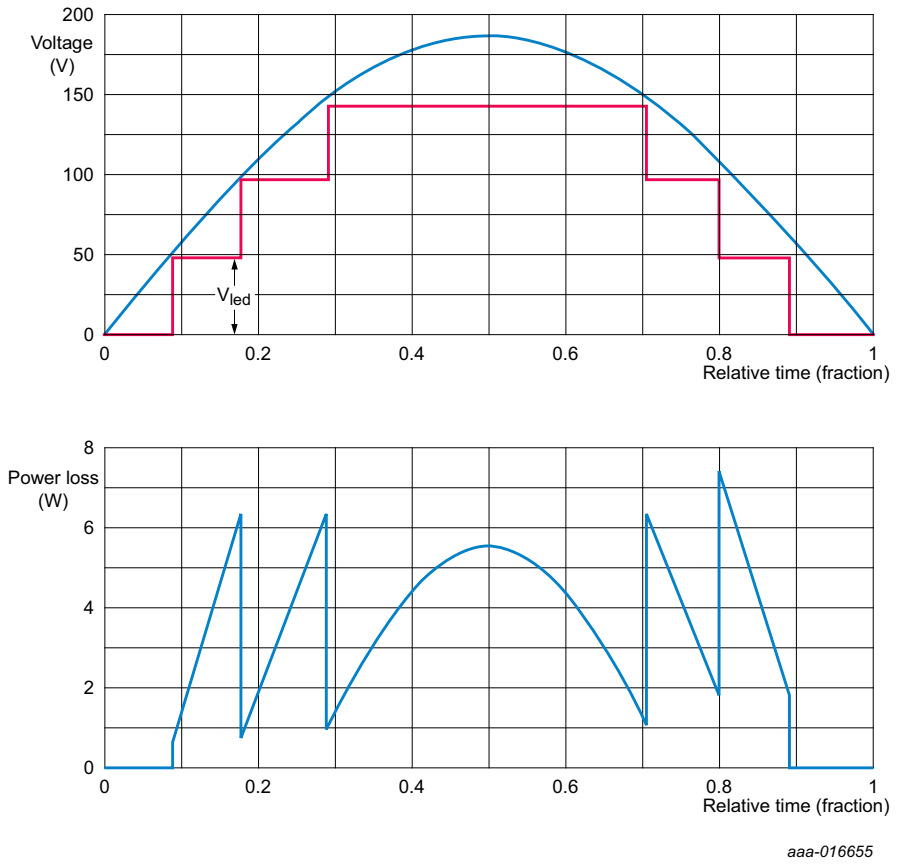

Fig 4. Mains voltage compared to the cumulative LED voltage and resulting dissipation in the LED driver

To prevent that the IC becomes a hot spot in the application, heat reduction resistors are added. These resistors allow a 40 % reduction of the dissipation in the LED driver IC. The resistors can be placed at a distance from the IC, so they provide a way for the dissipation to spread across the application.

Figure 5 shows the concept of the heat reduction resistors. Each LED current source is divided in an A and a B branch. An external resistor is placed in the B branch. When a string has turned on, current initially flows mostly through branch A. As the mains voltage increases, the mismatch between the cumulative LED voltage and the mains voltage increases as well. This additional voltage allows current to start flowing through the B branch. The transistors in the A and B branch are biased so that the transfer of current occurs automatically.

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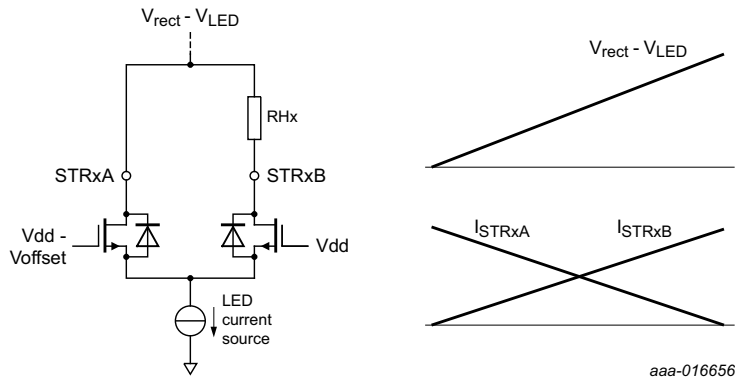

Fig 5. Heat reduction resistor

For V_{rect} = 120 V, P_{in} = 12 W, and I_{HVLCS} = 120 mA, a good value for the heat reduction resistor is: R_{Hx} = 350 Ω.

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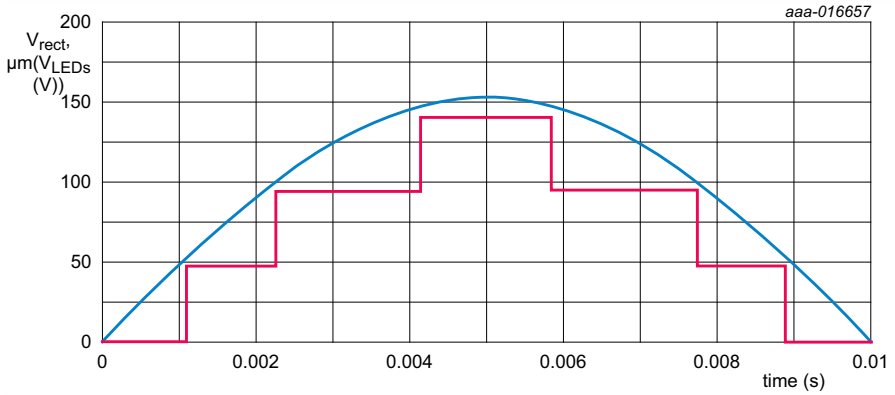
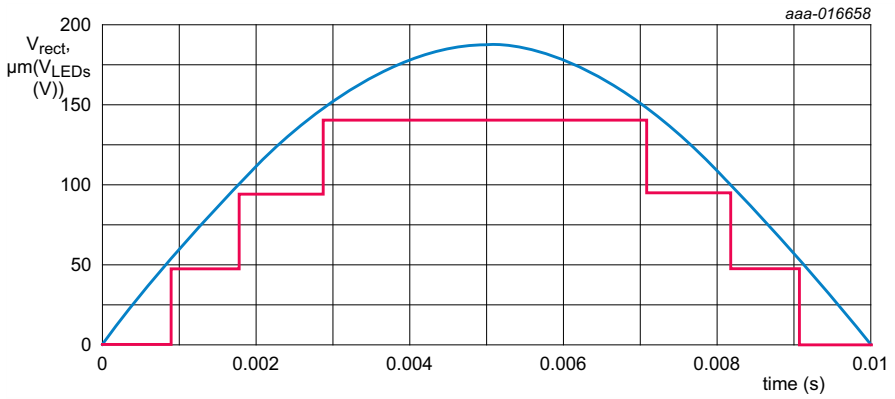
2.4 Limiting maximum dissipation and design for typical operation

Linear LED drivers normally have relatively poor line regulation because for higher mains voltages, the on-time of the LEDs increases. The result is a higher average LED current and a higher output power. Figure 6 shows this effect.

The thermal design of the lamp must be dimensioned for the highest power level, which is for V_{mains} = 132 V. Dimensioning in this way is undesirable because V_{mains} = 132 V is not the typical operating condition.



a. V_{rect} = 108 V (AC)



b. V_{rect} = 132 V (AC)

Fig 6. Mains waveform and cumulative LED

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To allow the design for the typical operating condition of V_{mains} = 120 V, the LED driving current is reduced when V_{mains} > 120 V. To achieve this LED driving current limitation, the feedback through the OV pin of the IC is used. The OV feedback limits the dissipation of the lamp for higher mains voltages (See Figure 7).

Fig 7. OV feedback used to limit the dissipation of the lamp for V_{mains} > 120 V

At what voltage the OV feedback starts, can be configured using Zener diode Z_{OV}. Resistor R_{OV} then sets the strength of the feedback. Figure 11 shows the connection of Z_{OV} and R_{OV}.

Typical values for Z_{OV} and R_{OV} are:

- Z_{OV} = 20 V
- R_{OV} = 360 kΩ

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2.5 Mains surge protection

The maximum rated voltage of the HV pins of the SSL6203TW at room temperature is 350 V. As the SSL6203TW targets the US market, the application has to withstand a 2.5 kV ring wave test, superimposed on a peak mains voltage of

$$V_{peak} = 132 \times \sqrt{2} = 187\ V.$$

As the power to be dissipated during the surge test is too high for the SSL6203TW to handle, external protections are required to protect the IC.

Figure 8 shows a proposed protection circuit. A large TVS is used as a primary protection. A small surge resistor creates some voltage drop for the secondary protection TVS. Finally, a small capacitor limits the dV/dt and the maximum voltage swing on the rectified mains. Place this capacitor as close to the IC as possible.

A Metal-Oxide Varistor (MOV) can also replace the large input TVS.

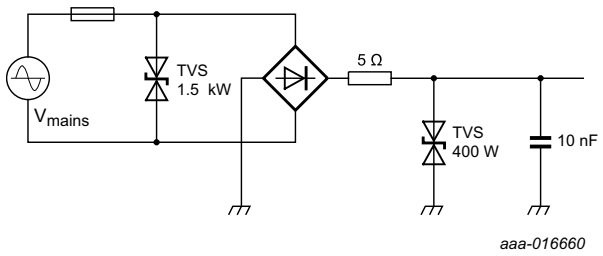

Fig 8. Proposed input protection circuit

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3. Applications

The NXP Semiconductors linear driver can be used with a mains voltage of 120 V (RMS). Three applications with varying performance levels are suggested here. All three solutions conform to standard mains surge and EMI requirements.

A 10 nF HV input capacitor is required from RECT to GND to ensure correct operation of the linear driver IC.

The NXP Semiconductors linear LED driver incorporates a smart bleeder for increased dimmer compatibility. This bleeder is only activated when insufficient mains voltage is available to support activation of an HV LED.

A single resistor R_{BLEED} sets the bleeder current I_{HVBCS} for each of the solutions. This resistor is connected between the IC voltage supply pins VDD1/2 and the bleeder current reference pin BLEED. To generate the bleeder current $I_{HVBCS} \approx 1000 \times I_{I(BLEED)}$, the reference current flowing into the BLEED pin is multiplied by approximately 1000.

$$I_{HVBCS} \approx (I_{I(BLEED)} + 2.5\ mA) \times 1000 \leq 45\ mA \quad (1)$$

The bleeder current must be ≤ 45 mA, as indicated by Equation 1.

The bleeder current I_{HVBCS} is sunk from the RECT pin. For more information about how the bleeder current is calculated, see the *SSL6203TW data sheet*. The resistor value that sets the bleeder reference current $I_{I(BLEED)}$ can be calculated with Equation 2:

$$R_{BLEED} = \frac{12.5}{I_{I(BLEED)}}\ \Omega \quad (2)$$

Figure 9 shows the phase-cut dimming waveforms of total input current (magenta), IHVBCS (yellow), mains voltage (blue) and STR3A (green). When the dimmer is off (i.e. when the mains voltage is zero), the bleeder only discharges the capacitive current from the dimmer. At the end of the mains cycle, when insufficient mains voltage is available to turn on one HV LED, the bleeder becomes fully active.

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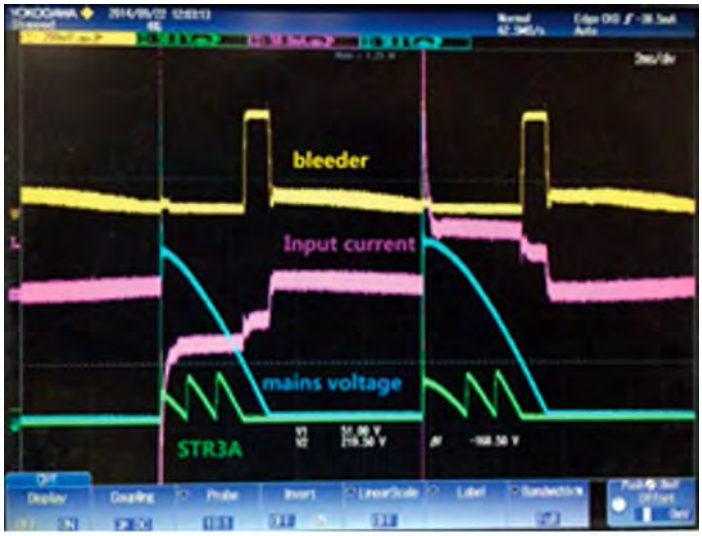
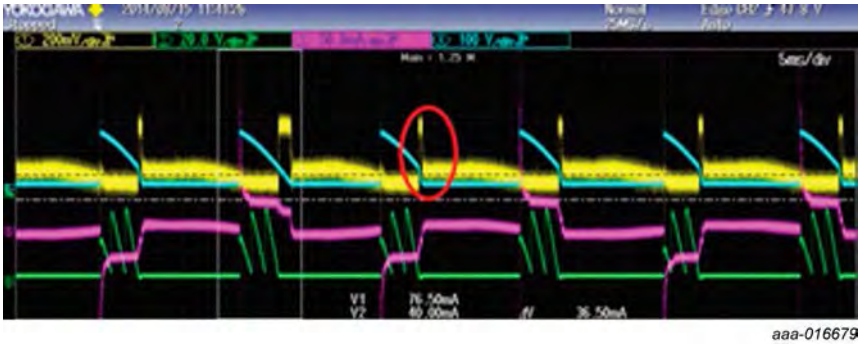


(1) Magenta = Input current
(2) Yellow = I_{HVBCS}
(3) Blue = Mains voltage
(4) Green = STRA3A

Fig 9. Phase-cut dimming waveforms showing when the bleeder is active

When insufficient bleeder current is set, shimmer or flutter can occur at certain dimmer angles for a phase-cut dimmer. Figure 10 show example waveforms of a dimmer showing this behavior. The discontinuity in the mains voltage indicates that the dimmer turns off because of insufficient bleeder current. As in some cycles the dimmer works properly and in other cycles it does not, shimmer or flutter can be observed.



(1) Magenta = Input current
(2) Yellow = I_{HVBCS}
(3) Blue = Mains voltage
(4) Green = STRA3A

Fig 10. Shimmer or flutter can occur when an insufficient bleeder current is set

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3.1 High-performance dimmable application

Figure 11 shows the high performance phase-cut dimmable application.

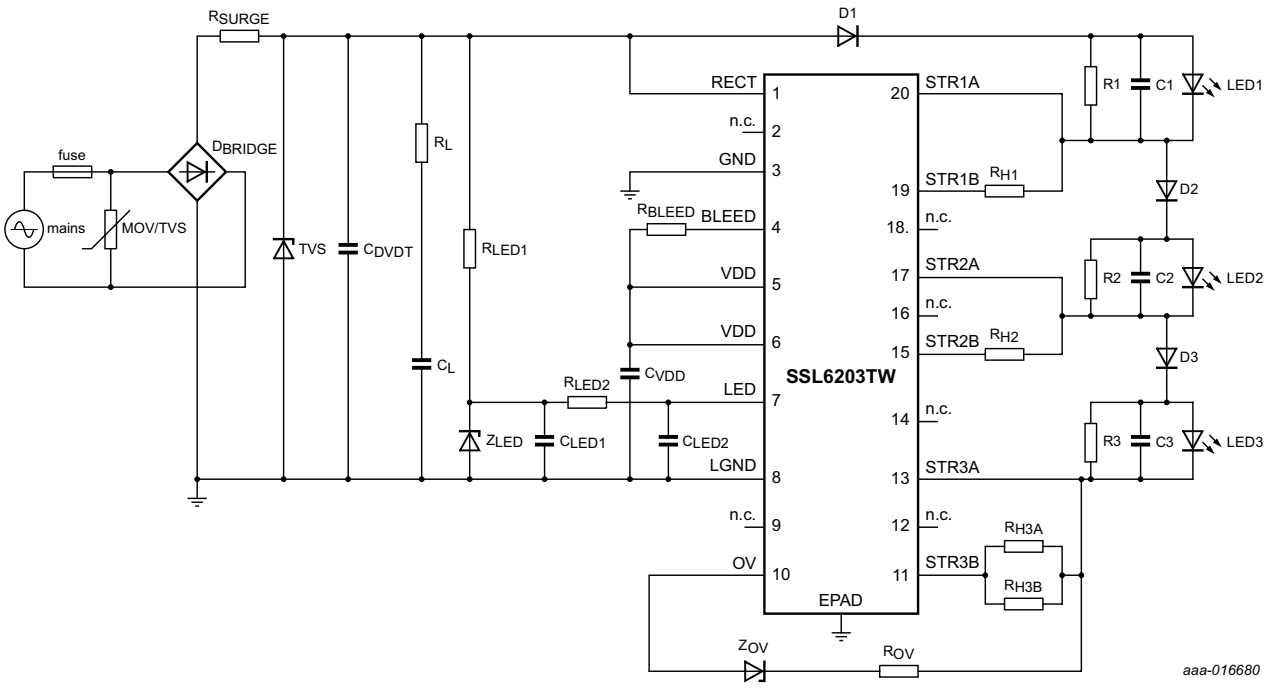

Fig 11. High-performance dimming application schematic

This application features a near-incandescent lamp dimming curve and a high quality of light through placement of capacitors C1, C2. and C3 in parallel with the LEDs. To prevent that capacitors C1, C2, and C3 are discharged at low mains voltages and when the switches are used, blocking diodes D1, D2. and D3 are required. Figure 12 shows the waveforms of the RECT, STR3A, and C3 ripple current when a capacitor of 100 μF is used. The remaining current ripple for this configuration is ±30 %.

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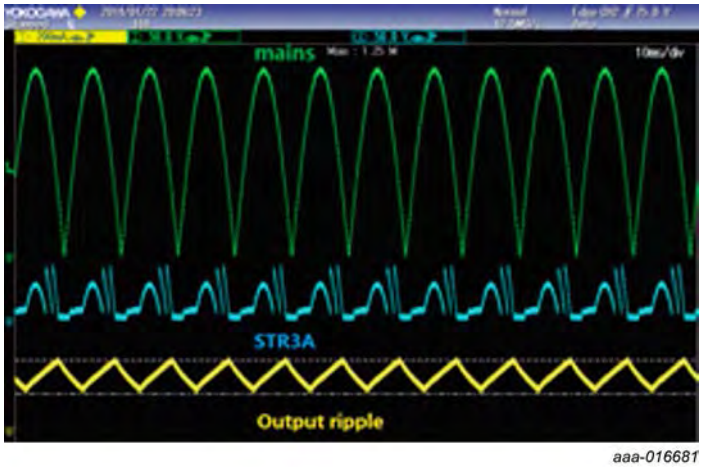

(1) Green = Mains current

(2) Blue = STRA3A

(3) Yellow = Output ripple

Fig 12. Ripple current of capacitor 3 (yellow) for a capacitance of 100 μF

Providing a reference current $I_{I(LED)}$ to the LED pin of the IC sets the LED current I_{HVLCS}. To obtain the LED driving current, i.e. $I_{LED} \approx 1000 (I_{I(LED)} + 17\ \mu A)$, this reference current and the internal reference current of about 17 μA are multiplied by approximately 1000.

For the high-performance application, the R_{LED1}, R_{LED2}, Z_{LED}, C_{LED1}, C_{LED2} network generates the $I_{ref(LED)}$. This network provides a reference current that scales with the average mains voltage. When phase-cut dimming is used, the average mains voltage decreases. I_{ref} follows and decreases the LED driving current. The result is a near-incandescent dimming curve (see Figure 13).

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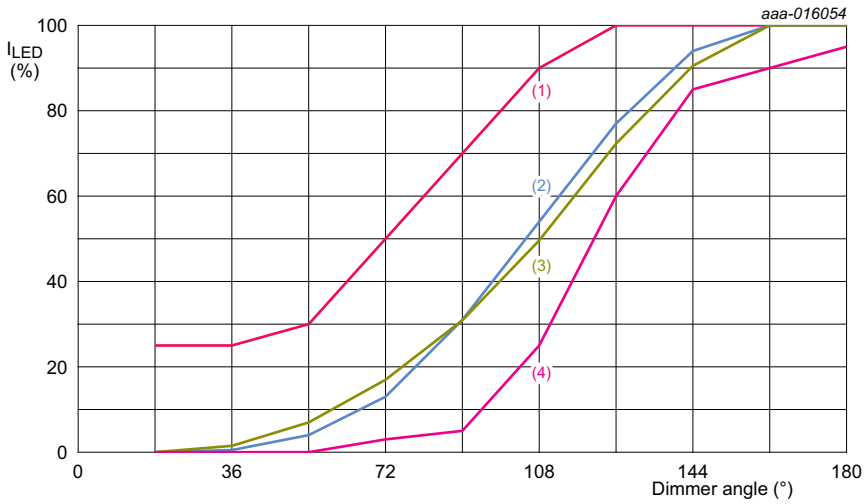

(1) Upper NEMA limit
(2) Incandescent
(3) SSL6203TW
(4) Lower NEMA limit

Fig 13. Dimming curve of the high-performance dimmable application

To trigger phase-cut dimmers correctly, an RC latch (components R_L and C_L) between the RECT and GND nodes is required. Typically, R_L = 1 kΩ and C_L = 68 nF.

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3.2 Low-cost dimmable application

Figure 14 shows the low-cost phase-cut dimmable application schematic. The main differences with the high-performance dimmable application are that the capacitors to improve light quality have been omitted and that $I_{I(LED)}$ is now generated with a single resistor to the IC voltage supply V_{DD}.

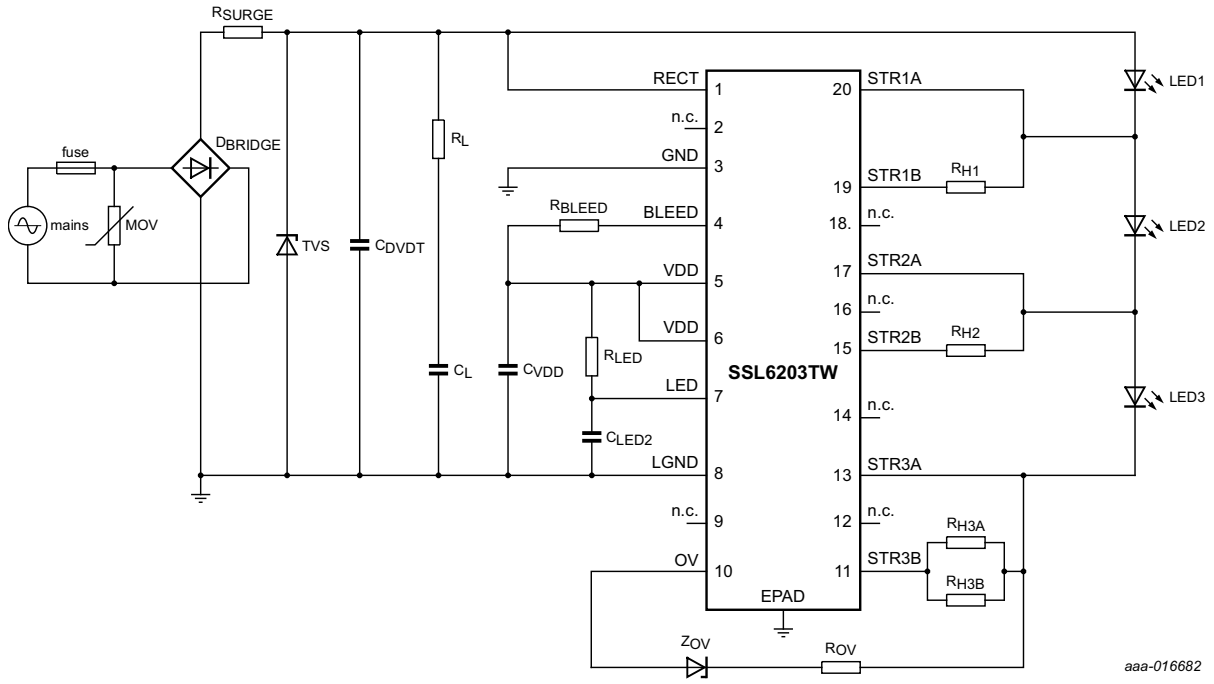

Fig 14. Low-cost dimmable application schematic

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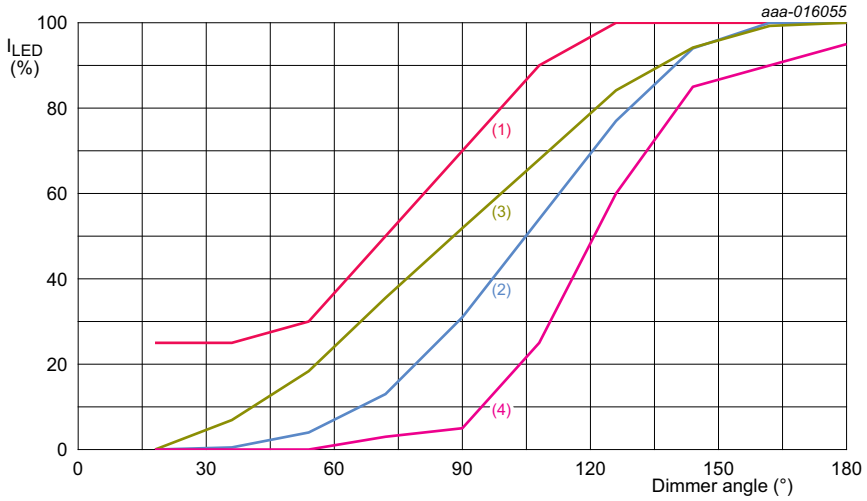
Figure 15 shows how the fixed $I_{I(LED)}$ reference current changes the dimming curve of the linear LED driver, which is according to the NEMA standard.



(1) Upper NEMA limit
(2) Incandescent
(3) SSL6203TW
(4) Lower NEMA limit

Fig 15. Low-cost dimmable application dimming curve

The LED driving current I_{HVLCS} can be estimated using Equation 3:

$$I_{HVLCS} \approx (I_{I(LED)} + 17\ \mu A) \times 1000 \leq 120\ mA \quad (3)$$

The LED driving current must be ≤ 120 mA as indicated by Equation 3.

The required value for R_{LED} can be set using Equation 4:

$$R_{LED} = \frac{11.25}{I_{I(LED)}}\ \Omega \quad (4)$$

Section 3.1 describes the setting of the bleeder current.

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3.3 Non-dimmable application

Figure 16 shows the non-dimmable application. For this application, the RC latch required to trigger phase-cut dimmers the resistor to set the bleeder reference current $I_{I(BLEED)}$ have been removed.

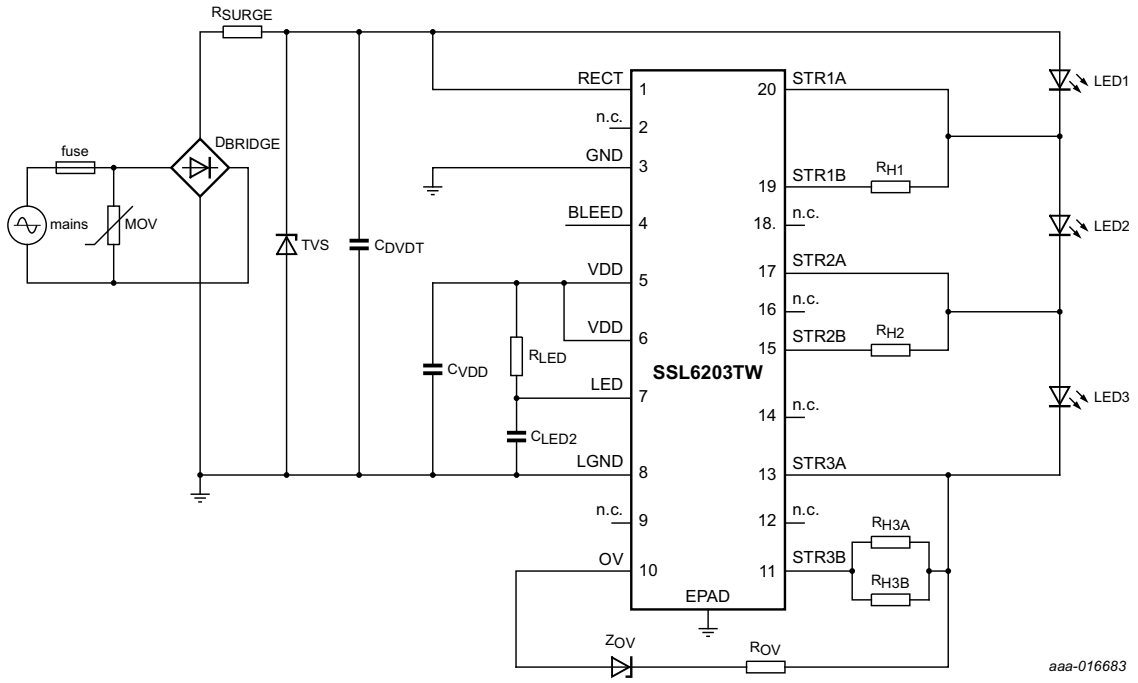

Fig 16. Non-dimmable application

The non-dimmable application is the lowest cost option for the NXP Semiconductors linear LED driver.

The BLEED pin can be left floating because for a non-dimmable application, no bleeder current is required. To ensure that the rectified mains node is properly discharged, a small bleeder current (1.2 mA) is still drawn from RECT.

Section 3.2 describes the setting of the LED driving current.

3.4 LED requirements

For the proposed A19 solution [2], three LED strings of 48 V each are used. The maximum voltage of one LED string depends on the mains input voltage. It can be calculated with Equation 5:

$$3 \cdot V_{LED} + 16 > V_{mains(peak)} \quad (5)$$

Example for a 120 V (AC) design with ±10 % variation:

- The typical $V_{mains(peak)}$: $\sqrt{2} \times 108$
- The typical V_{LED} for each string: $\frac{(\sqrt{2} \times 108 - 16)}{3} = 51\ V$

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For the best system efficiency, it is better to select an LED voltage at typical V_{mains} according to Equation 6:

$$3 \times (V_{LED} + 16\ V) > V_{mains}\ (typical) \quad (6)$$

Example for a 120 V (AC) design with ±10 % variation:

- The typical V_{mains}: $\sqrt{2} \times 120$
- The typical V_{LED} for each string: $\frac{(\sqrt{2} \times 120 - 21)}{3} = 48\ V$

For the low-cost solution without electrolytic capacitors, the peak current which is set by R_{LED} (as described in Section 3.2), is drawn through each LED string. For the high performance solution with electrolytic capacitors, the peak current that flows through the LED strings depends strongly on the selected size of the electrolytic capacitor.

The average LED current is the duty cycle multiplied with the maximum current through an LED string. When V_{LED} is 47 V, the duty cycle is approximately 0.57 for each string at typical mains Voltage, thus the average current is then 0.55 * I_{peak}.

The maximum average current through each LED string for a typical application (120 V (AC)/60 Hz) is therefore: $0.55 \times 120\ V = 68\ mA$.

Choosing V_{LED} = 51 V results in a high efficiency for V_{mains} > 120 V (AC). For V_{mains} < 120 V (AC), one string does not turn on and the efficiency reduces.

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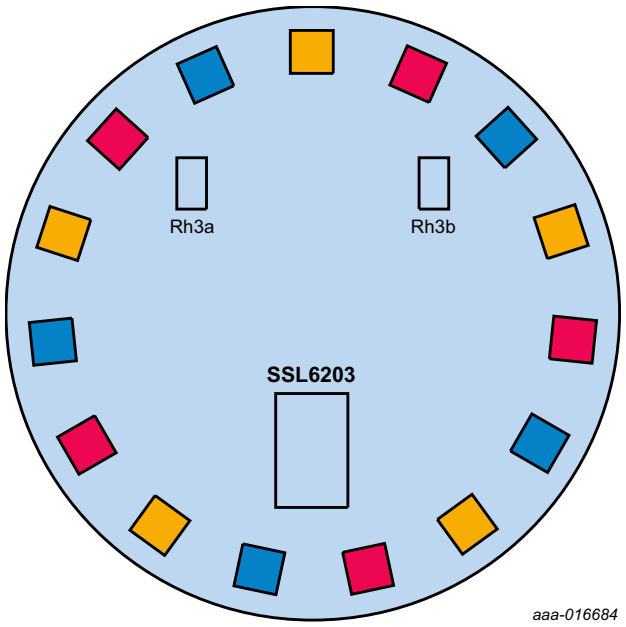
4. Layout

An LED driver based on the SSL6203TW is small enough to fit on an A19 LED plate. Some guidelines for the layout are provided here.

- For the best optical performance, interleave the LEDs of the 3 strings. Figure 17 shows the interleaving for 5 LEDs per string.
- Heat reduction resistors RH3A and RH3B dissipate most power (see Figure 17). Place them at a distance from the SSL6203TW because it dissipates a relatively large amount of power as well.
- Place C_{VDD} as close to the SSL6203TW as possible. When C_{VDD} is disconnected, the IC is not robust against high dV/dts on its input pins. To increase the robustness of the IC, place 2 V_{DD} capacitors that can handle half the capacitance as if one C is placed.
- Low thermal resistance from LED to heat sink is crucial for the best LED light efficiency. Thermal vias can be used underneath the LEDs and the SSL6203TW to transport heat towards the heat sink efficiently.
- For the best optical performance, an electrolytic capacitor can be placed on backside.



Worst-case dissipation:

(1) $P_{IC} \approx 1.3$ W
(2) $P_{rh1} \approx 0.2$ W
(3) $P_{rh2} \approx 0.3$ W
(4) $P_{rh3a} \approx 0.5$ W
(5) Prh3b ≈ 0.5 W

Fig 17. Placement guidelines for the SSL6203TW, heat reduction resistors, and LEDs

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5. Abbreviations

Table 1. Abbreviations

Acronym	Description
EMI	ElectroMagnetic Interference
LE	Leading-Edge (referring to an R or R_L dimmer)
LED	Light-Emitting Diode
PF	Power Factor
SSL	Solid-State Lighting
TE	Trailing-Edge (referring to an R_C dimmer)

6. References

[1] SSL6203TW data sheet — 120 V mains dimmable, 12 W linear LED driver

[2] UM10857 user manual — SSL6203DB1276 120 V 12 W linear LED driver

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